23

Application Guide

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23.1 INTRODUCTION

This chapter is an applications guide to nondestructive assay (NDA) techniques to aid the user in matching instruments with measurement problems. The figures and tables of this chapter refer to many of the measurement techniques described earlier in the book; several important active techniques are also included. Additional information on active NDA techniques is provided in the Nuclear Regulatory Commission (NRC) manual *Active Nondestructive Assay of Nuclear Materials,* by T. Gozani (Ref. 1). Detailed summaries of NDA measurement methods and results are provided in the NRC *Handbook of Nuclear Safeguards Measurement Methods,* edited by D. R. Rogers (Ref. 2).

Figure 23.1 is an overview of NDA techniques including examples of some common instruments associated with each technique. The figure illustrates the variety of techniques available to the assayist. In the various nuclear fuel cycles, plutonium and uranium appear in many forms, and this can often make it difficult for the user to select the appropriate technique for his measurement needs. This guide attempts to address this problem by summarizing the capabilities of the principal gamma-ray and neutron assay techniques (Section 23.2) and by providing a detailed table that matches nuclear materials with appropriate NDA instruments (Section 23.3).

This guide does not address irradiated fuel measurements, perimeter monitors, or attribute and holdup measurements; these subjects are covered in Chapters 18, 19, and 20.

23.2 CAPABILITIES OF SELECTED PASSIVE AND ACTIVE NDA TECHNIQUES

Gamma rays follow radioactive decay and carry energy information that uniquely identifies the nuclides present in the sample. This information is usually preserved by the detection process. The principal difficulty for gamma-ray assay is to accurately correct for sample attenuation. Gamma-ray attenuation increases with atomic number

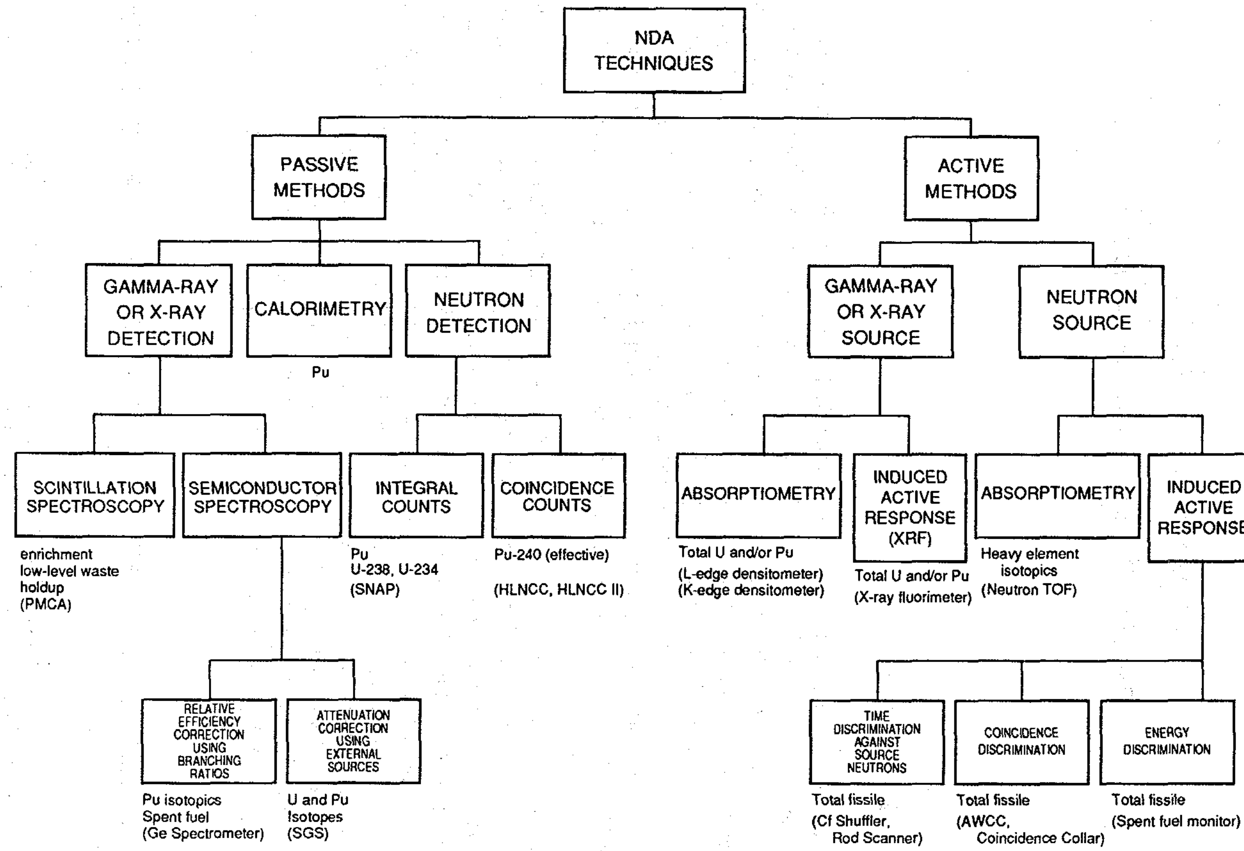

Fig. 23.1 An overview of passive and active NDA techniques, including the names of some common instruments.

and material density, so gamma-ray assay techniques work best for materials with low atomic number (<25) and low density (<1 g/cm^3). Neutrons carry less specific energy information, and even this is lost in the typical detection process. Neutron radiation does not provide information to identify the nuclear species present in the sample. On the other hand, neutrons penetrate dense, high-atomic-number materials (for example lead and uranium) with ease. They have more difficulty with very low atomic number materials, especially anything containing hydrogen, such as water or polyethylene. Gamma-ray and neutron assay techniques are, therefore, complementary because of their different sensitivities to density and material type. In general, passive assay techniques work well on plutonium samples because plutonium decay reactions (alpha decay and spontaneous fission) have high specific activities. The very low specific activities of the uranium decay modes often dictate the use of active measurement techniques.

The figures in this section summarize the accuracy that may be expected for the assay of a single sample using the principal NDA techniques. Figure 23.2 illustrates the "assayability" of various material forms using gamma-ray spectroscopy techniques. Homogeneous, low-density materials such as gases, solutions, and powders can be assayed most accurately. For these materials, gamma-ray assay is the technique of choice because the observed spectral peaks provide unique signatures that identify the nuclear material isotopes present and also yield a quantitative assay of the isotopic mass. It is important to note that gamma-ray spectroscopy provides a clear identification of the nuclear species in a sample, even in cases where the sample is too dense or too heterogenous to permit an accurate determination of mass.

For heterogeneous or dense materials where the gamma-ray attenuation is too high to permit accurate corrections, neutron assay techniques may be preferable. Figure 23.3 illustrates the "assayability" of different nuclear materials using neutron counting techniques. Most large samples of metal, oxide, and high-density scrap and waste require neutron-based techniques. Neutron assay accuracy is degraded if there is a high background from (α,n) reactions or if moderating materials such as moisture or combustible waste are present.

For the assay of plutonium, calorimetry provides a slower but more accurate assay alternative, which is insensitive to the presence of matrix materials (except that matrix materials may increase the assay time by increasing the time required to reach thermal equilibrium). Both calorimetry and neutron assays usually require knowledge of the isotopic composition of the plutonium being measured; gamma-ray spectroscopy provides one way to measure isotopic composition.

Figures 23.4 and 23.5 illustrate the range of performance for the most common gamma-ray and neutron assay techniques. In general, the gamma-ray techniques, where applicable, are more accurate than neutron techniques. Also, passive assay techniques are often more accurate than active assay techniques because the sample matrix can affect both the induced and the interrogating radiation, and the interrogating radiation can interfere with the assay radiation, thereby reducing sensitivity and precision.

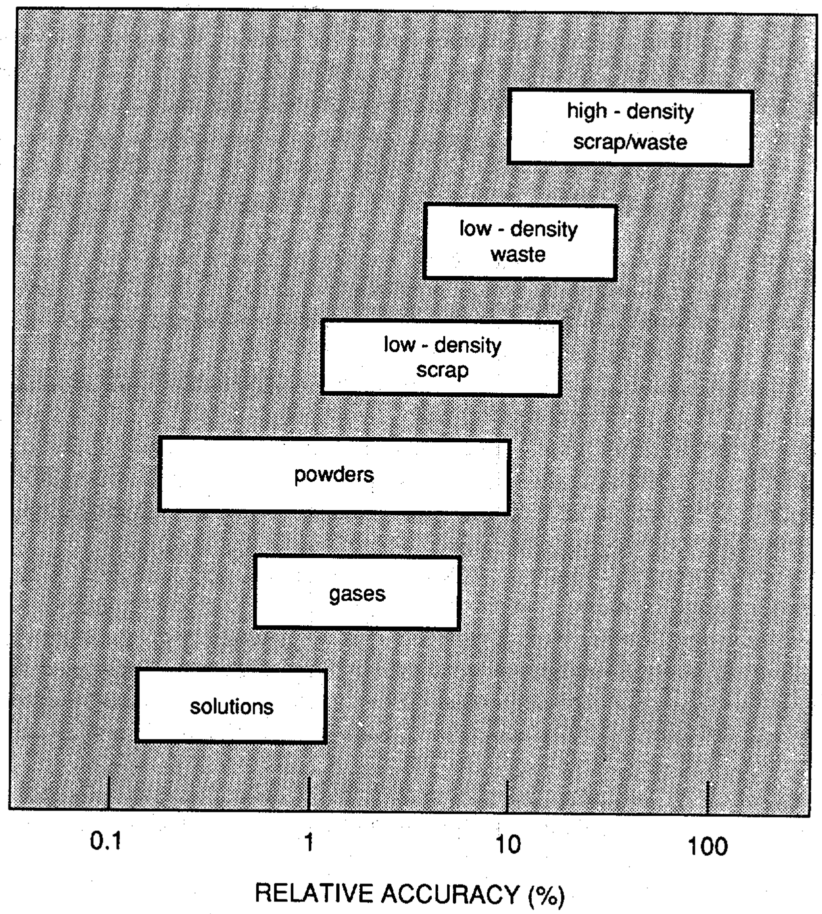

Fig. 23.2 *Sample "assayability" using gamma-ray spectroscopy techniques. By way of comparison, destructive analytical chemistry techniques routinely achieve accuracies in the range 0.05% to 0.5%.*

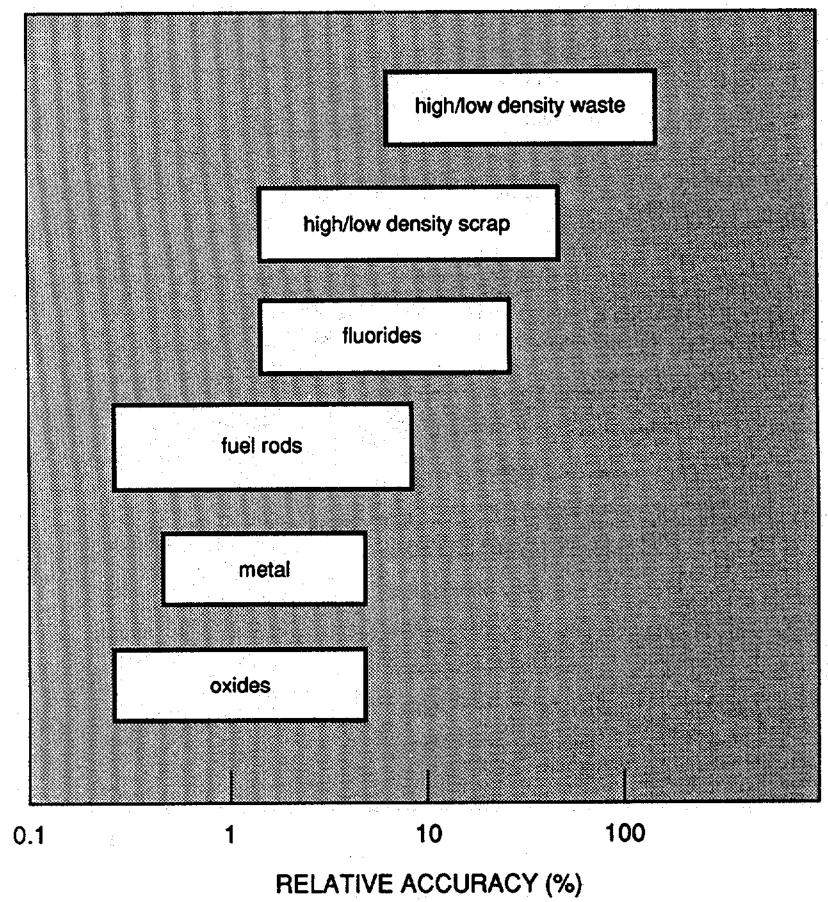

***Fig. 23.3** Sample "assayability" using neutron-based NDA techniques.*

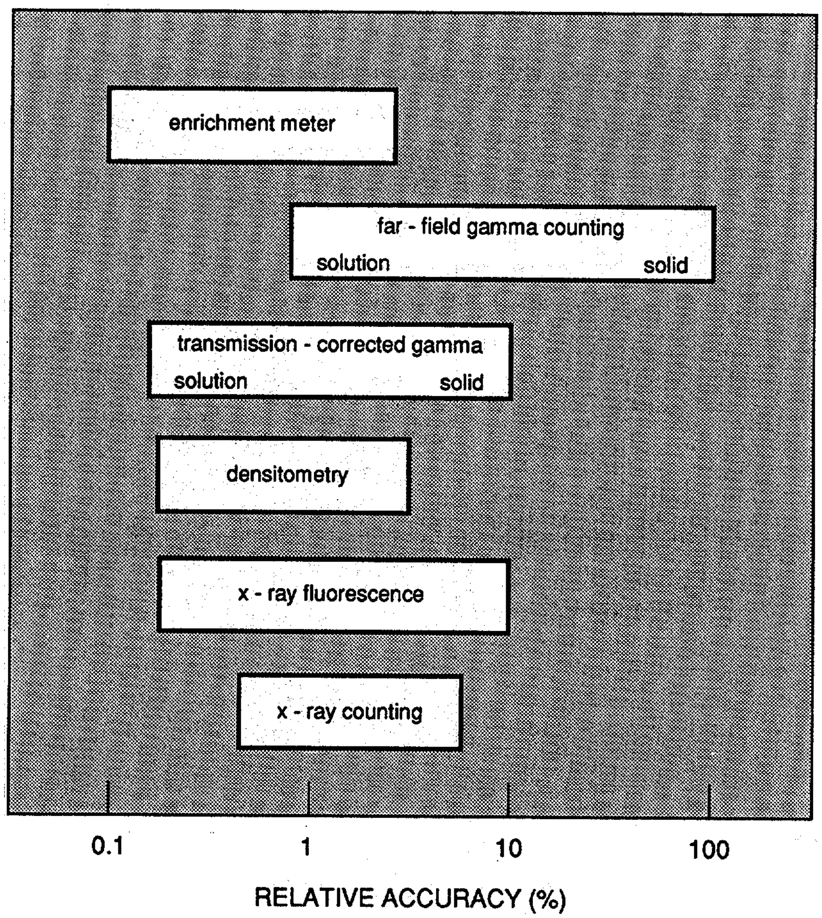

***Fig. 23.4** The range of performance for gamma-ray NDA techniques.*

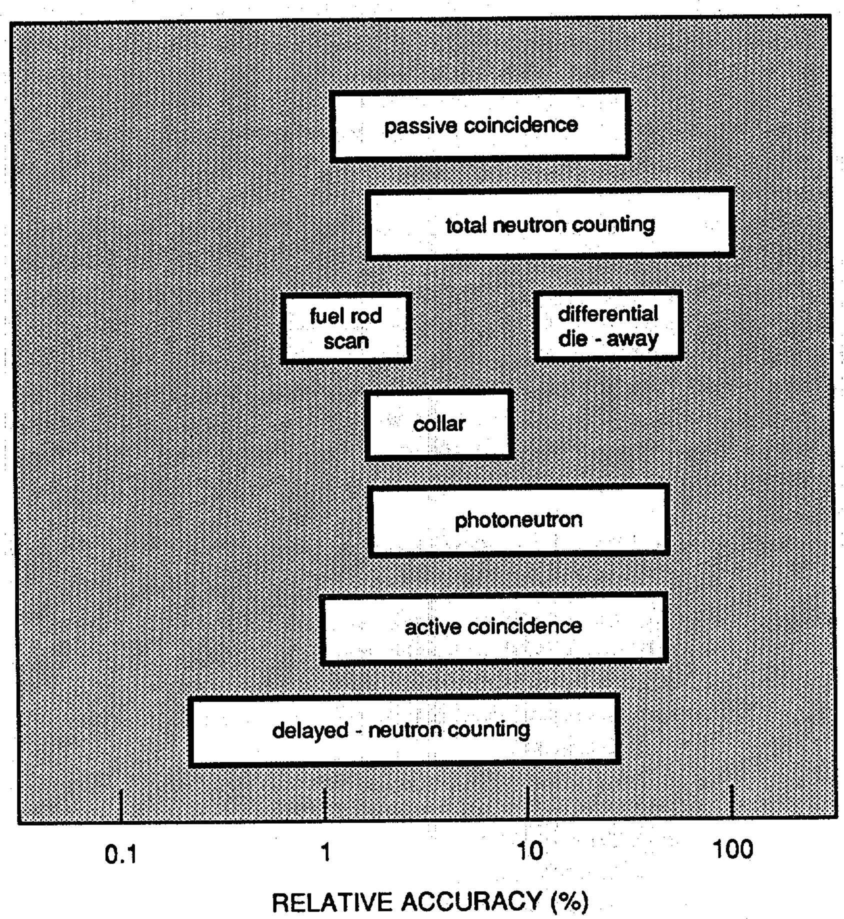

Fig. 23.5 The range of performance for neutron-based NDA techniques.

23.3 NUCLEAR MATERIAL TYPES AND APPLICABLE NDA TECHNIQUES

Table 23-1 provides a list of NDA techniques that may be applicable to a given measurement problem. In spite of its large size, Table 23-1 is not all-inclusive, and every entry is actually a generalization of many possible techniques. The table should serve as a starting point to guide the user toward a suitable technique. More detailed application tables are given in the *Handbook of Nuclear Safeguards Measurement Methods* (Ref. 2). An explanation of the table headings is given below.

Nuclear Material: Table 23-1 covers the following material types: plutonium, high-enriched uranium (HEU), low-enriched uranium (LEU), and mixed uranium and plutonium.

Material Form or Matrix: Table 23-1 covers metal, oxide, fluoride, solutions, fuel pellets and rods, and high- and low-density scrap and waste. In most cases, the assay approach for carbides is the same as for oxides. For fluorides, some assay techniques are suitable for PuF_6 or UF_6 gas and others are suitable for PuF_6, PuF_4, UF_6, or UO_2F_2 in either liquid, powder, or solid form. For neutron-based assay techniques, oxides have low (α,n) yields and fluorides have high (α,n) yields.

Scrap is relatively rich in nuclear material and is usually recycled, whereas the nuclear material content of waste is relatively low and can usually be discarded. Scrap and waste may be suitable for gamma-ray assay, if they have sufficiently low density.

NDA Technique: Table 23-1 covers the following NDA techniques or instruments:

gamma-ray:
- Far-field assay without transmission correction (MEGAS: MultiEnergy Gamma Assay System)
- Transmission-corrected assay viewing entire sample.
- Transmission-corrected segmented scan (SGS: Segmented Gamma Scanner)
- Enrichment meter (^{235}U concentration).
- Isotopic composition determination (Pu).
- K-edge densitometry.
- L_{III}-edge densitometry.
- X-ray fluorescence (K or L).

neutron:
- Neutron totals counting (SNAP: Shielded Neutron Assay Probe)
- Passive neutron coincidence counting (HLNCC: High-Level Neutron Coincidence Counter)
- Active neutron coincidence counting (AWCC: Active Well Coincidence Counter)
- Active neutron coincidence collar.
- Random driver (fast-neutron coincidence counting).

neutron: Neutron coincidence self-interrogation.
Californium shuffler (delayed neutron counting).
Photoneutron interrogation (PHONID: PHOtoNeutron Interrogation Device)
Differential die-away technique.

calorimetry: Plus isotopic measurement.

There are other NDA techniques that are not included in this list, such as the accelerator-based measurements described in Ref. 1.

For each nuclear material and matrix, only the most commonly used techniques are included in the table. The techniques are listed in the order of decreasing accuracy or frequency of use. The choice of technique may depend on the specific measurement problem and on factors such as cost, sample throughput, available space, etc.

Measured Isotopes: The NDA techniques listed in Table 23-1 may determine element or isotope mass or concentration. The user often requires supplemental information, usually isotopic composition, which may be available from the facility or from other destructive or nondestructive measurements. For calorimetric assay, *the accuracy stated in Table 23-1 includes the estimated accuracy of the isotopic measurement.*

Passive or Active: This column indicates whether the technique uses an external neutron or gamma-ray source to irradiate the sample. The neutron coincidence self-interrogation technique, which measures the fissions induced by (α,n) neutrons from internal reactions, is classified as passive.

Range: This column provides a very rough estimate of the applicable mass or concentration range of the NDA technique. The quoted lower limit is the measurability limit rather than the detectability limit, which may be considerably less than the mass given in the table. The range is stated in terms of the *element mass* even if only one isotope is measured.

Time: This is the approximate measurement time required to produce the stated precision.

Precision: This is the reproducibility of a single measurement stated, in percent, as one relative standard deviation. The precision is estimated for mid-range samples and, for active techniques, an optimum interrogation source strength is assumed.

Accuracy: The accuracy is stated, in percent, as one relative standard deviation, and includes the errors due to measurement precision, sample position, calibration, and instrument bias. For calorimetry, the estimated accuracy includes, and is often dominated by, the accuracy of the isotopic determination. The numbers quoted for scrap/waste assume some sorting and segregation into material categories and also assume the presence of few or no self-attenuating lumps of nuclear material.

Reference: References shown as numbers only refer to the section in this book where more detailed information can be found on a given measurement technique. Reference "x.y" refers to Section y in Chapter x. Other sources include Refs. 1 through 9.

Table 23-1. Guide to NDA techniques

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
Pu								
metal	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	4 h	0.3	0.3	21.9
	calorimetry/gamma isotopics	total Pu	P	10 - 6000 g	4 h	0.5	1 - 2	21.9
	neutron coincidence (HLNCC)	fertile	P	10 - 6000 g	300 s	0.5	1 - 4	17.2
	neutron totals (SNAP)	fertile	P	10 - 6000 g	30 s	1	2	15.2
	neutron coincidence (AWCC)	fissile	A	10 - 10000 g	1 h	5	5 - 10	17.3
	gamma isotopic	all but ^{242}Pu	P	0.1 - 10000 g	30 - 60 min	0.1 - (3 - 5)	0.1 - 1	8.7.5
oxide	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	4 - 6 h	0.3	0.3	21.9
	calorimetry/gamma isotopics	total Pu	P	10 - 6000 g	4 - 6 h	0.5	1 - 2	21.9
	neutron coincidence (HLNCC)	fertile	P	10 - 6000 g	300 s	0.5	1 - 3	17.2
	neutron coincidence (AWCC)	fissile	A	10 - 10000 g	1 h	5	10	17.3
	gamma isotopic	all but ^{242}Pu	P	0.1 - 10000 g	30 - 60 min	0.1 - (3 - 5)	0.1 - 1	8.7.5
PuF_4 powder	neutron totals	fertile	P	1 - 500 g	30 s	1	2 - 5	15.2
	neutron coincidence self-interrogation	fissile	P	50 - 1000 g	600 s	1	5-10	20.4
solutions	transmission-corrected gamma	^{239}Pu conc.	P	0.001 - 400 g/L	1000 s	0.2 - 1	0.2-1	6.9.4
	K-edge densitometry	Pu conc.	A	40 - 500 g/L	1500 s	0.5	0.2 - 1	9.4
	L_{III}-edge densitometry	Pu conc.	A	5 - 100 g/L	1500 s	0.5	0.2 - 1	9.4
	x-ray fluorescence	Pu conc.	A	0.1 - 400 g/L	300 s	0.5	0.3 - 1	10.5
	neutron coincidence (HLNCC)	fertile	P	1 - 500 g	300 s	0.5	1 - 5	17.2

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
Pu								
fuel rods	neutron coincidence (pin-tray counter)	fertile	P	10 - 1000 g	600 s	1	0.5 - 2	Ref. 8
fuel assembly	neutron coincidence (breeder counter)	fertile/fissile	P	1 - 9 kg	300 s	0.2	0.5 - 2	Ref. 9
scrap/waste (high density)	neutron coincidence (HLNCC)	fertile	P	10 - 6000 g	300 s	1 - 5	2 - 30	17.2
	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	8 - 16 h	0.3	0.5	22.4
	calorimetry/gamma isot.	total Pu	P	10 - 6000 g	8 - 16 h	0.5	1 - 2	22.4
	neutron coincidence self-interrogation	fissile	P	50 - 3000 g	1000 s	1	10	20.4
scrap/waste (low density)	segmented gamma scan (SGS)	^{239}Pu	P	1 - 1400 g	1000 s	1	1 - 5	6.9.5
	far-field gamma count	^{239}Pu	P	1 - 1400 g	300 s	1 - 2	1 - 5	6.9
	neutron coincidence (HLNCC)	fertile	P	10 - 6000 g	1000 s	5	5 - 30	17.2
	x-ray count (MEGAS)	^{239}Pu	P	10 μg - 10 g	200 s	10	10 - 50	Ref. 2
	differential die-away	fissile	A	5 mg - 10 g	1000 s	1	30	Ref. 3
HEU								
metal	californium shuffler	fissile	A	1 g - 10 kg	1000 s	0.1	0.5 - 5	Ref. 4
	neutron coincidence (AWCC)	fissile	A	10 g - 10 kg	1000 s	0.5 - 5	1 - 5	17.3
	random driver	fissile	A	50 g - 10 kg	1000 s	1 - 5	1 - 5	Ref. 5
	photoneutron interrogation (PHONID)	fissile	A	1 g - 1 kg	200 s	0.1 - 3	1 - 5	Refs. 6, 7
	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.1 - 1	0.1 - 0.5	7.3

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
HEU								
oxide	transmission-corrected gamma	^{235}U	P	0.1 - 200 g	300 s	1	1 - 2	6.9.3
	enrichment meter	^{235}U (%)	P	200 g - 20 kg	100 s	0.1 - 1	0.1 - 0.5	7.3
	californium shuffler	fissile	A	1 g - 20 kg	1000 s	0.1	0.3 - 3	Ref. 4
	neutron coincidence (AWCC)	fissile	A	10 g - 20 kg	1000 s	1 - 5	1 - 5	17.3
	random driver	fissile	A	50 g - 10 kg	1000 s	1 - 5	1 - 5	Ref. 5
	photoneutron interrogation (PHONID)	fissile	A	1 g - 3 kg	200 s	0.1 - 3	1 - 5	Refs. 6, 7
	neutron totals (SNAP)	^{234}U	P	100 g - 10 kg	500 s	2 - 5	5 - 10	15.2
UF_6 gas	transmission-corrected gamma	^{235}U	P	0.1 - 100 g	1000 s	0.7	1	7.5
UF_6 liquid	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.1 - 1	0.25	7.3
UF_6 solid	neutron coincidence (AWCC)	fissile	A	100 - 1000 g	1000 s	1 - 5	1 - 5	Ref. 6
	neutron coincidence self-interrogation	fissile	P	1 - 20 kg	600 s	0.5	3	17.3
	neutron totals	^{234}U	P	10 g - 10 kg	200 s	2	2 - 5	15.2
	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.2 - 1	0.5 - 5	7.7
solutions	transmission-corrected gamma	^{235}U conc.	P	0.001 - 400 g/L	1000 s	0.1 - 0.2	0.2 - 1	6.9
	K-edge densitometry	U conc.	A	40 - 500 g/L	1500 s	0.5	0.2 - 1	9.4
	L_{III}-edge densitometry	U conc.	A	5 - 100 g/L	1500 s	0.5	0.2 - 1	9.4
	x-ray fluorescence	U conc.	A	0.1 - 400 g/L	300 s	0.5	0.3 - 1	10.5

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
HEU								
fuel pellets	random driver	fissile	A	50 g - 10 kg	1000 s	1 - 5	1 - 5	Ref. 5
	neutron coincidence (AWCC)	fissile	A	10 g - 10 kg	1000 s	1 - 5	1 - 5	17.3
	californium shuffler	fissile	A	1 g - 10 kg	1000 s	0.1 - 2	0.3 - 3	Ref. 4
	photoneutron interrogation (PHONID)	fissile	A	1 g - 3 kg	200 s	0.1 - 3	1 - 5	Refs. 6, 7
	gamma-ray well counter	^{235}U	P	0.1 - 10 g	300 s	0.2	0.1 - 0.5	7.3
	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.5	0.25 - 1	Ref. 2
fuel rods	neutron coincidence collar	fissile	A	100 g - 10 kg	1000 s	0.5	2 - 4	17.3
	fuel rod scanner	fissile	A	1 - 100 g	30 s	0.1	1	Ref. 1
scrap/waste (high density)	californium shuffler	fissile	A	1 g - 10 kg	1000 s	0.1 - 2	2 - 25	Ref. 4
	neutron coincidence (AWCC)	fissile	A	10 - 1000 g	1000 s	1 - 5	5 - 25	17.3
	random driver	fissile	A	50 - 1000 g	1000 s	1 - 5	5 - 25	Ref. 5
scrap/waste (low density)	segmented gamma scanner (SGS)	^{235}U	P	1 - 200 g	1000 s	1	2 - 10	6.9.5
	transmission-corrected gamma	^{235}U	P	1 - 200 g	300 s	1	2 - 20	6.9.3
	differential die-away	fissile	A	5 mg - 10 g	1000 s	1	30	Ref. 3
	californium shuffler	fissile	A	1 - 1000 g	1000 s	0.5	2 - 25	Ref. 4
	neutron coincidence (AWCC)	fissile	A	10 - 1000 g	1000 s	1 - 5	5 - 25	17.3

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
LEU								
metal	neutron totals (well counter)	^{238}U	P	1 - 500 kg	1000 s	1	2 - 3	15.4
	neutron coincidence (well counter)	^{238}U	P	2 - 500 kg	1000 s	2 - 5	2 - 5	15.4
	neutron coincidence (AWCC)	fissile	A	1 - 10 kg	1000 s	5	5 - 10	17.3
	californium shuffler	fissile	A	10 g - 10 kg	1000 s	1	1 - 2	Ref. 4
	photoneutron interrogation (PHONID)	fissile	A	10 - 1000 g	200 s	0.1 - 3	1 - 5	Refs. 6, 7
	enrichment meter	^{235}U (%)	P	200 g - 200 kg	300 s	0.2 - 1	0.2 - 0.5	7.3
oxide	enrichment meter	^{235}U (%)	P	200 g - 200 kg	300 s	0.2 - 1	0.2 - 0.5	7.3
	neutron coincidence (AWCC)	fissile	A	1 - 10 kg	1000 s	5	5 - 10	17.3
	californium shuffler	fissile	A	10 g - 10 kg	1000 s	1	1 - 2	Ref. 4
	photoneutron interrogation (PHONID)	fissile	A	10 - 1000 g	200 s	0.1 - 3	1 - 5	Refs. 6, 7
UF_6 gas	transmission-corrected gamma	^{235}U	P	5 - 100 g	1000 s	0.7	1 - 3	7.5
UF_6 liquid	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.25 - 1	0.25 - 0.5	7.3
UF_6 solid	neutron coincidence (AWCC)	fissile	A	1 - 10 kg	1000 s	1	2 - 5	Ref. 6
	enrichment meter	^{235}U (%)	P	200 g - 500 kg	300 s	1	1 - 5	7.7
solutions	transmission-corrected gamma	^{235}U conc.	P	1 - 400 g/L	1000 s	0.5	0.5	6.9
	K-edge densitometry	U conc.	A	40 - 500 g/L	1500 s	0.5	0.2 - 1	9.4
	L_{III}-edge densitometry	U conc.	A	5 - 100 g/L	1500 s	0.5	0.2 - 1	9.4
	x-ray fluorescence	U conc.	A	0.1 - 400 g/L	300 s	0.5	0.3 - 1	10.5

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
LEU								
fuel pellets	neutron coincidence (AWCC)	fissile	A	1 - 10 kg	1000 s	5	5 - 10	17.3
	californium shuffler	fissile	A	1 g - 10 kg	1000 s	1	1 - 2	Ref. 4
	photoneutron interrogation (PHONID)	fissile	A	10 - 1000 g	200 s	0.1 - 3	1 - 5	Refs. 6, 7
	gamma-ray well counter	^{235}U	P	1 - 10 g	300 s	0.1 - 3	0.1 - 0.5	7.3
	enrichment meter	^{235}U (%)	P	200 g - 20 kg	300 s	0.5 - 1	0.25 - 1	Ref. 2
fuel rods	neutron coincidence collar	^{235}U	A	100 g - 10 kg	1000 s	1	2 - 4	17.3
	neutron coincidence collar	^{238}U	P	1 - 10 kg	1000 s	2	5	17.3
	fuel rod scanner	fissile	A	1 - 100 g	30 s	0.1	1	Ref. 1
scrap/waste (high density)	californium shuffler	fissile	A	1 g - 10 kg	1000 s	1	5 - 20	Ref. 4
	neutron coincidence (AWCC)	fissile	A	1 - 10 kg	1000 s	5	10 - 50	17.3
	transmission-corrected gamma	^{238}U	P	100 - 5000 g	1000 s	1	2 - 20	6.9.3
	neutron totals (well counter)	^{238}U	P	10 - 500 kg	1000 s	1	2 - 5	15.4
scrap/waste (low density)	segmented gamma scanner (SGS)	^{235}U	P	1 - 200 g	1000 s	1	2 - 10	6.9.5
	transmission-corrected gamma	^{235}U	P	5 - 200 g	1000 s	1	2 - 20	6.9.3
	differential die-away	fissile	A	5 mg - 10 g	1000 s	1	30	Ref. 3

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
U & Pu								
oxide	neutron coincidence (HLNCC)	fertile Pu	P	10 - 6000 g	300 s	0.5	1 - 2	17.2
	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	4 - 8 h	0.3	0.5	21.9
	calorimetry/gamma isotopics	total Pu	P	10 - 6000 g	4 - 8 h	0.5	1 - 2	21.9
	neutron coincidence (AWCC)	fissile Pu, U	A	50 - 2000 g	1000 s	3	5	17.3
	gamma-ray spectroscopy	all but ^{242}Pu	P	0.1 - 6000 g	1 h	0.1 - (3 - 5)	0.2 - 1	8.7
	gamma-ray spectroscopy	Pu/U mix ratio	P	0.1 - 6000 g	300 s	1	2	7.8
solutions	transmission-corrected gamma	^{239}Pu/^{235}U	P	1 - 400 g/L	1000 s	0.5	0.2 - 1	6.9
	K-edge densitometry	Pu & U conc.	A	40 - 500 g/L	1500 s	0.5	0.2 - 1	9.4
	L_{III}-edge densitometry	Pu & U conc.	A	5 - 100 g/L	1500 s	0.5	0.2 - 1	9.4
	x-ray fluorescence	Pu & U conc.	A	0.1 - 400 g/L	300 s	0.5	U:0.3/Pu:2	10.5
fuel pellets	neutron coincidence (HLNCC)	fertile Pu	P	1 - 2000 g	300 s	0.5	1 - 2	17.3
	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	8 - 16 h	0.3	0.5	21.9
	calorimetry/gamma isotopics	total Pu	P	10 - 6000 g	8 - 16 h	0.5	1 - 2	21.9
	neutron coincidence (AWCC)	fissile Pu, U	A	50 - 2000 g	1000 s	3	5	17.3
	gamma-ray spectroscopy	all but ^{242}Pu	P	0.1 - 6000 g	1 h	0.1 - (3 - 5)	0.2 - 1	8.7
	gamma-ray spectroscopy	Pu/U mix ratio	P	0.1 - 6000 g	300 s	1	2	7.8

Table 23-1. (Continued)

Material Form or Matrix	NDA Technique	Measured Isotopes	Passive or Active	Range	Time	Precision (%)	Accuracy (%)	Reference
U & Pu								
fuel rods	neutron coincidence collar	fissile Pu, U	A	100 g - 10 kg	1000 s	1	2 - 4	17.3
	neutron coincidence collar	fertile Pu	P	100 - 6000 g	1000 s	1	1 - 2	17.3
	calorimetry/isotopes	total Pu	P	10 - 200 g	1 h	0.4	1 - 3	22.5
	fuel rod scanner	fissile	A	1 - 100 g	30 s	0.1	1	Ref. 1
scrap/waste (high density)	neutron coincidence (HLNCC)	fertile Pu	P	10 - 6000 g	300 s	1 - 5	5 - 30	17.2
	calorimetry/mass spec. isot.	total Pu	P	10 - 6000 g	8 - 16 h	0.3	0.5	22.4
	calorimetry/gamma isotopics	total Pu	P	10 - 6000 g	8 - 16h	0.5	1 - 2	22.4
	neutron coincidence (AWCC)	fissile Pu, U	A	50 - 2000 g	1000 s	5	10 - 50	17.3
scrap/waste (low density)	segmented gamma scanner (SGS)	^{239}Pu	P	1 - 1400 g	1000 s	0.5 - 2	2 - 20	6.9.5
	transmission-corrected gamma	^{239}Pu	P	1 - 1400 g	300 s	1	2 - 25	6.9.3
	neutron coincidence (HLNCC)	fertile Pu	P	10 - 6000 g	1000 s	5	5 - 30	17.2
	differential die-away	fissile Pu, U	A	5 mg - 10 g	1000 s	1	30	Ref. 3

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